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Comparison of energy management controls for fuel cell applications

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Abstract

Nowadays, fuel cell (FC) is seen like one of the main energy generators for the future. Indeed, it could be used for many different applications thanks to its goods performances. Nevertheless, the present high cost of a FC requires an optimal power flow of the power provided by the FC to make its development easier. So, the FC must fit each application fulfilling the imposed requirements in an optimal way.

As a consequence, the energy management made by the power interface of the FC based generator appears as a vital element: it regulates the power flow between the FC and the auxiliary energy storage. Consequently, it has a major influence on the size of this storage element.

This paper focuses on this control level. It presents three algorithms for the energy management developed by the authors. Each of the algorithms optimizes one criterion for the generator. The controls allow a good rate performances/simplicity. Furthermore, they give a good overview of the existing algorithms.

The paper tests and compares the three controls with three applications, which are the best adapted ones concerning the use of FC. The data of the applications are obtained from real installations. The comparison is done thanks to simulation.

This work has been realized in the framework of the European project FEBUSS.

Keywords: Energy management; Control; FC applications

1. Introduction

The fuel cell (FC) looks likely to play a main part in power generators thanks to its good performances. It is expected to be used for very different applications: stationary, transport and portable applications [1–4].

Because of the large scale of possible applications, the control of the power interface of a FC based generator is a fundamental aspect, as it determines the working mode of the entire generator. This control must be well adapted indeed to the selected application to provide good working conditions of the FC as well as an outstanding energy management [5–7]. Moreover, the present high cost of the FC makes the optimization of the power generated by the FC essential.

The control of the power interface can be divided into several different control levels depending on their function. The "highest level" – the global control generating the FC current reference – is the key for the energy management. It determines the power flow in function of the defined criteria, which can be related to many different working aspects. So, it allows taking advantage of the strong points of FC compared to the classical energy sources. As a consequence, a well-adapted energy management makes the development of this technology easier.

The energy management also plays an important role for determining the size of the energy storage or storage element (SE). As the dynamic response of the FC is not fast enough to supply the power demand instantaneously, it must be associated with an auxiliary energy source, usually known as SE. This SE can be batteries, supercapacitors, flywheel, ... depending on the case and implies an additional cost and a limit for the FC development. A good energy management system should reduce the size of the SE to a minimum and so the economical cost of the generator.

Taking into account all theses aspects, the paper focalizes on this control level. It presents and describes three controls developed by the authors for a FC based generator. The paper illustrates their influence on the FC working mode. Moreover, the controls are compared in the case of real applications.

The three controls have been selected as they represent a general selection of existing algorithms. Each of them is centered on one aspect of the FC based generator.

- The first one is based on an on-line optimization to reduce the hydrogen consumption (HC).

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- The second one is focused on the global efficiency of the FC.
- The last one tries to minimize the size of the SE.

The data for the loads have been obtained from real installations [1]. The comparison between the algorithms is done through simulations using the simulation tool Matlab Simulink.

In a first part, we describe the energy management with all its functions. Afterward, we present the three chosen algorithms. Then, we give the results we got thanks to simulation.

2. Energy management

The main goal of the energy management is to determine the optimal power flow between the FC and the SE in order to provide the power demanded by the load, P_{Load}.

This optimal power flow is determined in function of some criteria defined a priori which depend mainly on the application. Here, are the main criteria:

- HC,
- size of the SE,
- advised working mode of the FC and of the SE,
- power efficiency,
- reliability,
- pollution emissions,
- required hardware to implement and
- availability to other applications.

Some of these criteria have contradictory influences on the power flow. As a consequence, the energy management will be the result of a compromise between the selected aspects.

In addition to these criteria, the energy management must guarantee a correct state of charge of the SE at every instant, which must always be in a given interval. In order to allow this, the power flow calculated by the optimizing algorithm can be modified thanks to an additional factor depending on the state of charge.

The algorithm of the energy management needs some specific information to determine the optimal power flow. The main inputs of this algorithm are usually:

- The load power.
- The state of charge of the SE.

Other aspects conditioning the energy management are now analyzed (Fig. 1).

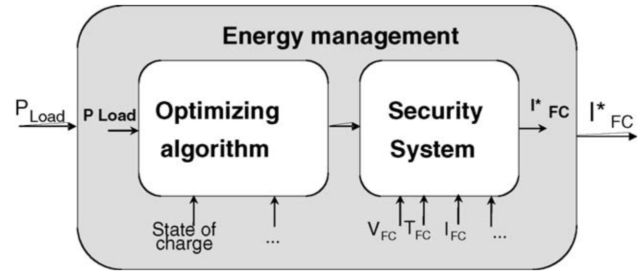

Fig. 1. Scheme of the energy management control.

2.1. The security system

The security system is usually included in the energy management [7]. It can limit the FC reference calculated by the optimal algorithm depending on the working conditions. So, regarding the energy management, the security system is the most important element for the transient response of the FC generator.

The security system can easily be separated from the optimizing algorithm, as its role is quite different. We will consider the security system as out of our scope and the paper will focus on the steady state of the FC generator. We will consider that the security system guarantees good working conditions for the generator during transients.

2.2. The applications and the structure of the power interface

The energy management is conditioned by the power interface, which regulates the power flows. However, the power interface depends mainly on the chosen applications.

Taking into account some previous work [1,8], we have selected some applications on which the paper focuses as they seem to be the best adapted ones to a possible commercialization of the FC. Here, they are:

- urban bus,
- tramway and
- back-up for one office building.

In these applications, the generator needs a nominal power roughly equal to 100 kW. The tramway can need several 100 kW modules. So, the net power of the FC we used is 100 kW. It is generated with a 300 A current.

The power interface shown on Fig. 2 is usually used for these applications. It is composed of three converters with different roles:

- An inverter for the connection to the application. It works like a voltage source supplying the energy demanded by the load.
- A classical Boost converter connected to the FC. It regulates the FC power calculated by the algorithm of the energy management.
- A bidirectional converter for the connection of the SE to the bus. The SE with its converter regulates the bus voltage.

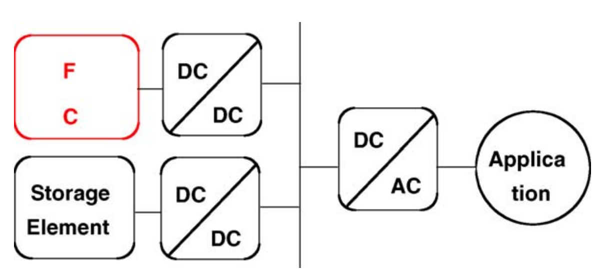

Fig. 2. Scheme of the power interface.

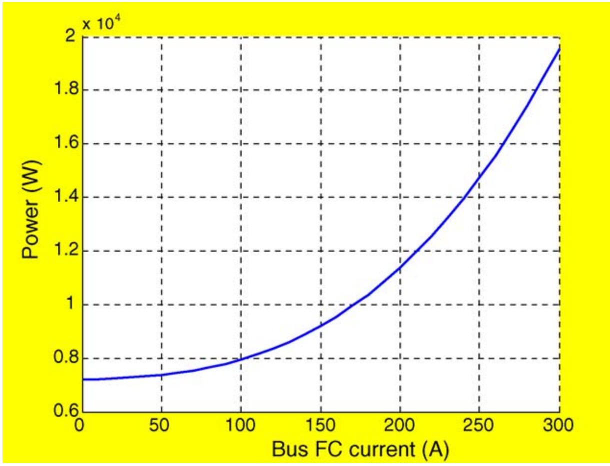

Fig. 3. Auxiliaries power consumption.

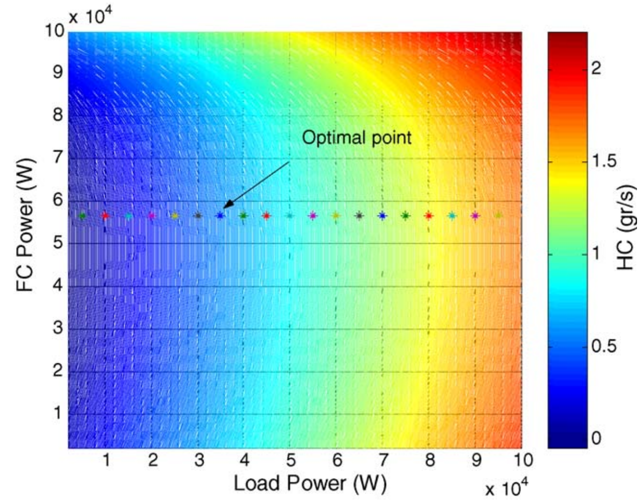

Fig. 4. Equivalent HC ($P_{FC\_Avg} = 30$ kW).

The control of power inverters composing the interface uses classical correctors. Reference [8] presents a more detailed description of the power interface.

2.3. The structure of the FC generator

Another aspect conditioning the energy management is the structure of the power generator, which depends on the selected applications.

Its dynamic response as well as the efficiency largely depends on the used auxiliaries. For example, the way to supply the oxygen or hydrogen can absorb a high percentage of the FC power [9].

The FC generator used for our applications is supplied by pure hydrogen using high pressure tanks. So that it is the oxygen supply through the compressor, which limits the dynamic response of the FC. It is a key element when designing the security system. Besides, the compressor is the most important auxiliary: it consumes 10% of the nominal power and its consumption depends on the FC power. The other auxiliaries: pumps, fan, . . . consume a constant power of 7.5 kW. Fig. 3 shows the consumption of all the auxiliaries. As the security system is out of our scope, the models of the FC auxiliaries used in our analysis are steady state ones and they do meet all the requirements of our study.

3. On-line optimization of the hydrogen consumption

The main goal of this algorithm is to reduce the HC of the FC as much as possible. This control is based on previous studies [10,7]. The HC, E_{H_2} in (g s^{-1}), is defined by (1):

$$E_{H_2} = \frac{N_C \cdot I_{FC} \cdot M_{H_2}}{2 \cdot F} \qquad (1)$$

where N_C is the number of cells connected in series, I_{FC} the output FC current, M_{H_2} the molar mass of dihydrogen (2 g mol^{-1}) and F is the Faraday constant (96485 C).

Its principle is based on the optimal energy management between the FC and the SE at each instant in order to reach the global optimum. The instantaneous optimal point is calculated using a deterministic optimizing algorithm in Matlab. This algorithm determines the FC power.

To evaluate the HC at each instant, we use the concept of an "equivalent consumption", $E_{H_2\_Eq}$; the total needed hydrogen is the sum of the hydrogen taken by the FC at that moment and of the hydrogen, which the FC will have to supply or save later. With this principle, the global HC to optimize, $E_{H_2\_Eq}$ can be written as follows:

$$\text{Val}_{Opt} = E_{H_2\_Eq} = E_{H_2}(P_{FC}) + \frac{E_{H_2}(P_{FC\_Avg})}{\eta_{SE}} \cdot \frac{P_{Load} - P_{FC}}{P_{FC\_Avg}} \qquad (2)$$

where Val_{Opt} is the value to be optimized, P_{FC} the power to be provided by the FC during the next period, P_{FC_Avg} the power transferred from the FC to the SE and η_{ES} is the power efficiency of the SE. $E_{H_2}(P_X)$ is the HC for the power P_X.

However, (2) must be modified, as it always leads towards the same point, even if the load changes. This is because there is no limit time to recover the energy supplied or absorbed by the SE [8]. Fig. 4 illustrates this. Moreover, this equation does not ensure a right state of charge of the SE.

To solve that, a term depending on the instantaneous state of charge $\text{State}_{t=i}$, is added to the fitness function in order to ensure a correct state of charge. As this aspect is taken into account during the optimizing process, it does not alter the "original" optimum very much. This is quite an improvement compared to some previous studies.

Furthermore, the P_{FC_Avg} is determined on-line applying a filter to the instantaneous demand. Thanks to this, this control can be easily transferred to any other application: it does not need any preliminary work to fix this value to the average load power.

In consequence, the final fitness function is as shown below:

$$\text{Val}_{Opt} = E_{H_2\_Eq} + k_e \cdot \frac{\text{State}_{t=i}}{\text{State}_{t=0}} \cdot \frac{P_{Load} - P_{FC}}{P_{SE\_Avg}} \qquad (3)$$

where $\text{State}_{t=0}$ is the initial state of charge and P_{SE_Avg} the nominal SE power and k_e (g H_2) is a tuning parameter determined in

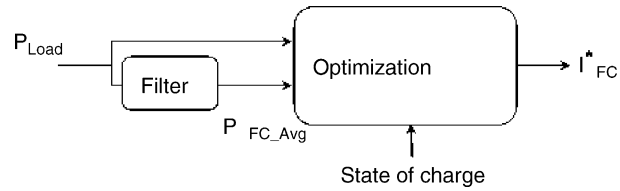

Fig. 5. Scheme of the on-line optimizing algorithm.

an empirical way which gives the sensitivity of the fitness function in relation to the SE state and is therefore a key parameter for the stability of the system.

The main advantages of this process regarding other existing controls are its performances and its simplicity. Also, it proposes some solutions to facilitate the implementation of this control algorithm. Moreover, it can be easily transferred to any other application.

Fig. 5 shows the global scheme of this energy management strategy.

4. Global efficiency

The aim of this control is to make the FC work at its maximal efficiency working point. This control represents a simpler energy management than the previous one in order to reduce the HC. The power efficiency takes only into account the electrical efficiency of the generator. The next equation illustrates it:

$$\eta_{FC} = \frac{P_{FC}}{P_{FC} + P_{Aux}(P_{FC})} \quad (4)$$

where P_{Aux} is the instantaneous electrical power absorbed by the auxiliaries depending on the instantaneous net electrical power provided by the FC.

This control is based on the curve giving the efficiency versus the FC current shown on Fig. 6. It is obtained using Eq. (4). In that way, we get a very simple method to determine the electrical efficiency of the generator without any a priori knowledge of the generator: we have determined a logical algorithm which guides the system towards the maximal efficiency point. Table 1 shows how the FC current reference is increased or reduced in function of the variations of the FC current and the FC efficiency.

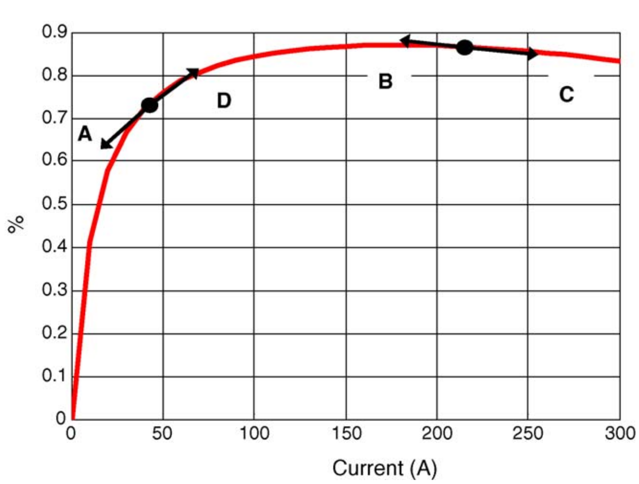

Fig. 6. FC power efficiency vs. FC current.

Table 1
Logical control table

	$\frac{dI_{FC}}{dt}$	
	−	+
$\frac{d\eta_{FC}}{dt}$		
−	A: ↑ I_{FC_REF}	C: ↓ I_{FC_REF}
+	B: ↓ I_{FC_REF}	D: ↑ I_{FC_REF}

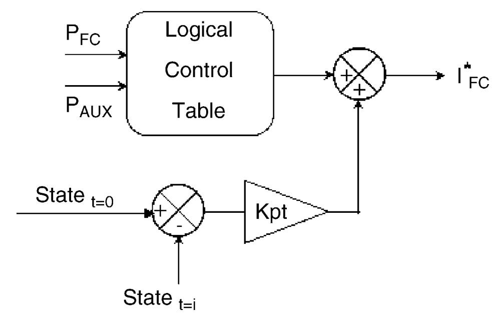

Fig. 7. Scheme of the global efficiency algorithm.

The value of the current variation depends on a compromise between the stability and the performances. This value determines the precision: higher the value is, smaller the precision is. However, a very small value can cause oscillations and the system is very slow.

One of the main advantages of this control is its robustness; it does not require any knowledge of the system—no power losses model, for example. It is also very simple to implement.

However, this control has to be complemented with a term depending on the state of the SE in order to ensure a good operation. We have implemented this additional term thanks to a signal proportional to the state of charge. Fig. 7 shows the global scheme of the control.

5. Energy management based on classical correctors

The main goal of this control is to reduce the size of the energy storage as much as possible. Nowadays, in some applications, the economical cost of the SE represents an important part of the total cost; that is why we propose this original control exploiting the dynamics of the FC to the utmost of its ability: the FC must try to supply the instantaneous power demanded by the load.

This control uses a classical proportional corrector whose reference is the initial state of charge of the SE. Its output is added to the current demanded by the load. In order to improve the transient response of the system, the FC reference also depends on the instantaneous power provided by the SE. Fig. 8 shows the scheme of this algorithm.

The main advantages of this strategy are the size of the required energy storage and its simplicity. Moreover, it does not need any knowledge of the system.

Nevertheless, with this strategy, the FC has to follow the load instantaneously, which could imply a reduction of its working

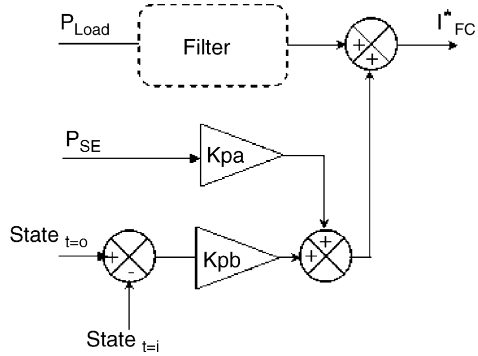

Fig. 8. Scheme of the energy management based on classical correctors.

life. To avoid this, a filter can be included to eliminate the very fast variations of reference (see Fig. 8). It must be a low pass filter, a first order one ($20\,\mathrm{dB\,dec^{-1}}$) could be suitable, but it depends on the FC generator.

However, this solution increases the size of the energy storage so that the cut off frequency should be determined by a technical–economical analysis taking into account the cost of the SE, the lifetime of the FC and of the SE.

6. Simulation results

The energy strategies are the same for the three applications. This allows to test their adaptability.

The selected criteria to compare the controls are: the size of the SE, the amount of the HC and the average efficiency. This average efficiency, η_{Ave} is defined considering the energy generated by the FC, W_{FC} in kJ, (5):

$$\eta_{\mathrm{Ave}}=\frac{\langle\eta_{\mathrm{FC}}\rangle}{W_{\mathrm{FC}}}=\frac{K_{\mathrm{W}}\cdot\int_0^{T_{\mathrm{Foct}}}\eta_{\mathrm{FC}}(t)\,\mathrm{d}t}{T_{\mathrm{Foct}}\cdot W_{\mathrm{FC}}} \quad (5)$$

where T_{Foct} is the working time, $\langle\eta_{\mathrm{FC}}\rangle$ the average efficiency of the FC without taking into account the generated energy and K_{W} is an adjustable constant in order to get final values of η_{Ave} around 1, in our case, K_{W} is equal to 100.

The final state of charge of the energy storage element is also another criterion. In our case, it is not guaranteed that the final state will be the same that the initial one. This is because the three controls determine the FC reference on-line without any a priori tuning. Even more, the used loads are intentionally stopped just after a high demand power demand so that we can analyze their performances in case of sudden stops.

However, we have taken into account this value to calculate the final HC. This lets compare correctly the HC. These values are shown in the next tables in parenthesis.

Table 2
Power characteristics of the load

	Tramway (kW)	Urban bus (kW)	Office building (kW)
Average power	70	59	36
Maximal power peak	200	169	94
Minimal power peak	−115	−60	0

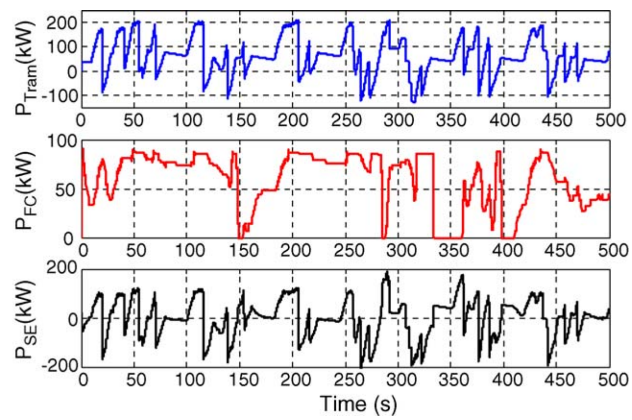

Fig. 9. Results of the algorithm focused on the HC for a tramway.

In order to make the understanding of the results easier, we only present the characterizing curves obtained with one algorithm for each application.

Due to the simulation time, we have worked on a 500 s cycle, which is enough to include the different situations and the constraints. At the beginning of the simulations, the state of charge of the SE is equal to 70% of its capacity.

6.1. Tramway

The main characteristics of this load are shown in Table 2 and on Fig. 9. This load is not the whole load of a tramway, but the one corresponding to one FC module powering a tramway. This load is characterized by a high rate between the minimal and maximal load power.

The results show how each control presents the best values concerning the aspect on which they are focused (Table 3). It validates their principles of working. Nonetheless, this performance is paid in terms of worse values concerning the other aspects. As we have said, the energy management must be the result of a compromise.

Due to the recuperation periods, the SE is used by all the algorithms like an energy source complementary to the FC.

Table 3
Comparison of the results for the tramway

Energy strategy	η_{Ave}	HC (g)	Final state	Size of the SE	
				Energy (kJ)	Power (kW)
On-line optimization H_2	1.277	558.9 (558.6)	−21 kJ, 70.28% (−0.32 g)	2091, −2141	189, −200
Global efficiency	1.371	590 (582.1)	−500 kJ, 75.81% (−7.85 g)	2573, −2125	165, −200
Classical correctors	1.169	638.7 (638.8)	3 kJ, 69.94% (0.047 g)	1643, −383	114, −195

Table 4
Comparison of the results for the urban bus

Energy strategy	η_{Ave}	HC (g)	Final state	Size of the SE	
				Energy (kJ)	Power (kW)
On-line optimization H_2	1.518	496.6 (537.3)	2598 kJ, 47.33% (40.7 g)	3384, −269	126, −144
Global efficiency	1.521	517.6 (536.6)	1230 kJ, 52.63% (19.3 g)	2125, −1824	135, −153
Classical correctors	1.383	556.5 (603.7)	3010 kJ, 42.63% (47.2 g)	3300, −134	76, −110

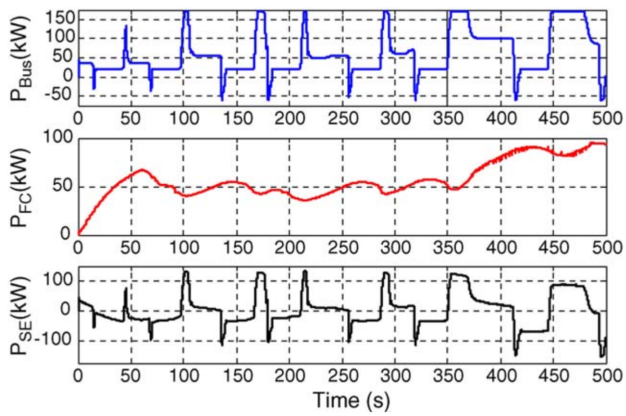

Fig. 10. Results of the algorithm focused on the efficiency for a urban bus.

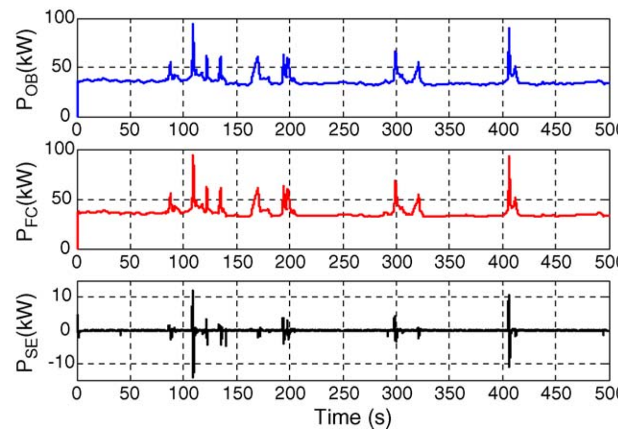

Fig. 11. Results of the algorithm based on the classical correctors for a office building.

The results obtained with the algorithm focused on the HC are shown on Fig. 9. The control does not make the generator follow the instantaneous power of the tramway, P_{Tram}. In fact, the FC oscillates around its optimal point; it only changes, when the SE, P_{SE}, requires it.

So this control makes the SE absorb the high and low dynamics of the load as much as possible. This leads to an increase of the size of the SE.

6.2. Urban bus

The load is presented in Table 4 and in Fig. 10. It is very similar to the one of a tramway, as it shows recovery periods. This bus load is characterized by a sudden stop to test it.

The obtained results are characterized by the same aspects as in the precedent case which confirms the validity of the proposed algorithms. The final state of the SE is clearly affected by the sudden stop in all cases.

The control focused on the global efficiency presents slow dynamics (see Fig. 10). Indeed, the FC is “isolated” from the load changes, as the control takes advantage of the recovery periods to compensate the acceleration ones. Thanks to this, this control strategy is less sensible to blunt stops, even if it needs bigger energy storage.

6.3. Office building

This load is very different from the previous ones: there is no recovery period (cf. Table 5 and Fig. 11). In this case, the control cannot separate the response of the FC from the dynamics of the load, because the recovery periods do not compensate the acceleration ones.

Despite these considerations, the results show that the controls are well adapted. This validates their utilization for stationary applications. However, the control focused on the global efficiency proves to be less performing because of low dynamics.

As Fig. 10 shows it, the control based on the classical correctors makes the FC follow the load as much as possible, So that the SE must only supply the instantaneous differences; it does not try to isolate the dynamics of the load from the dynamics of the FC. Consequently, the size of the SE is reduced to its minimum.

In conclusion, all these results validate the proposed algorithms for the transport as well as for the stationary applications.

Table 5
Comparison of the results for the office building

Energy strategy	η_{Ave}	HC (g)	Final state	Size of the SE	
				Energy (kJ)	Power (kW)
On-line optimization H_2	2.253	291.7 (290)	−50 kJ, 78.15% (−0.78 g)	0, −184	55, −55
Global efficiency	2.171	300.8 (295.4)	−347 kJ, 95.20% (−5.4 g)	232, −413	54, −32
Classical correctors	2.263	290.5 (290.5)	9 J, 69.96% (0 g)	8, −769	11, −14

Moreover, they illustrate the importance of the energy management for a FC based generator. They also show that there is no optimal algorithm optimizing all the criteria. However, we can say that some algorithms are better adapted than others for some particular cases.

7. Conclusion

Nowadays, FC is a very promising energy generator, thanks to its performances for many applications. Nevertheless and because of the large range of applications, the control of the FC is vital in order to make the development of the FC easier.

The FC generator must optimize the generated power. Among possible options for that purpose, the paper has focused on the energy management.

We have presented three algorithms we developed. They give a good overview of existing algorithms. They have been tested in simulation with real applications. The paper has shown that they fulfill the requirements satisfactorily.

There are several possibilities for future research. The first one is the optimal tuning of the proposed energy management. This step is necessary in order to exploit the optimal FC characteristics. It could be done focusing on one application only or several applications.

Another future step could be the implementation of the proposed algorithms on a real generator using a FC. It will allow their validation on real cases.

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